To increase controllability of a large flexible antenna by modal optimization

Feng Wang *, Pengpeng Wang, Wenjian Jiang

Xi'an Institute of Space Ratio Technology, Xi'an, China

*Corresponding author e-mail: 502748270@qq.com

Abstract. Large deployable antennas are widely used in aerospace engineering to meet the envelop limit of rocket fairing. The high flexibility and low damping of antenna has proposed critical requirement not only for stability control of the antenna itself, but also for attitude control of the satellite. This paper aims to increase controllability of a large flexible antenna by modal optimization. Firstly, Sensitivity analysis of antenna modal frequencies to stiffness of support structure and stiffness of scanning mechanism are conducted respectively. Secondly, Modal simulation results of antenna frequencies are given, influences of scanning angles on moment of inertia and modal frequencies are evaluated, and modal test is carried out to validate the simulation results. All the simulation and test results show that, after modal optimization the modal characteristic of the large deployable antenna meets the controllability requirement well.

1. Introduction

For dimension constraint of satellite fairing, large antennas are usually designed to be deployable. During launching period, the deployable antenna is stowed on the satellite panel, and deploys to the working configuration while in orbit. To avoid probable shadowing between antenna and satellite, large deployable antennas always have deployable arms or similar parts, the deployable arm should move to somewhere away from the satellite firstly before the antenna reflector could deploy to its desired shape[1,2].

With deploying of the large antenna, moment of inertia of the structure is increasing while modal frequency of the structure is decreasing, which will reduce the structural ability to resist external disturbance. Especially for large high precision mesh antenna, weak external disturbance may results in unacceptable distortion of the reflector and worsen pointing performance. Also, flexibility of the structure proposes rigorous requirement for the satellite attitude control design. To decoupling dynamic response between large deployable antenna and the satellite, three commonly used methods are available: Firstly, to increase the antenna modal frequency, usually the first frequency of the antenna is required to be two times greater than that of the satellite. Structural topology optimizations, adoption of high modulus material, reinforcement of the link stiffness are widely used in engineering [3]. Secondly, to reduce the satellite disturbance input. Disturbance of the satellite usually comes from the high rotation of rotary parts, ignition of propeller, motion of movable parts and thermally induced vibration of large flexible parts. Dynamic unbalance control, motion speed control and vibration isolation of flexible parts are applicable solutions [4, 5]. Thirdly, introduction of the vibration control strategy. Passive vibration control can increase structural damping by usage of viscoelastic material, active vibration control reduces dynamic response by smart structure combined with intelligent algorithm, while active and passive integration control combines merits of passive and active control methods, and can suppress structural vibration in a relatively wide frequency range [6-9]. However, as vibration control strategy has risks of failure and reduces reliability of the structure, and is not so widely used in aerospace applications so far. To increase controllability of large flexible antennas, much attention still focuses on how to increase the structural modal frequency yet.

As shown in Figure1, a large deployable antenna mainly consists of three parts: flexible mesh reflector, equipment container and deployable arm. Equipment container provide mounting base of the electronic equipments and acts as link part between the reflector and arm. To increase the structural stiffness, the deployable arm is in triangle configuration.

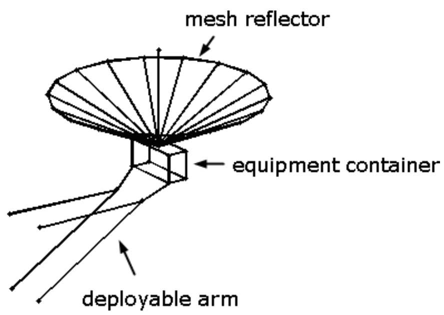


Figure1. Configuration of the larger deployable antenna

At stow status, the deployable arm is stowed and locked, and to realize the deployable function, four joints are used in the structure. Also for scanning requirement, a scanning mechanism is allocated between the equipment container and the deployable arm, and the mechanism could rotate about two orthotropic axes, which correspond to pitch (from -10 °to 25 °) and azimuth axis (from -10 °to 10 °) of the satellite respectively. The high flexibility and low damping of antenna has proposed critical requirement not only for stability control of the antenna itself, but also for attitude control of the satellite. According to the requirement of satellite control subsystem, the first resonant frequency of the large deployable antenna should no less than 1 Hz.

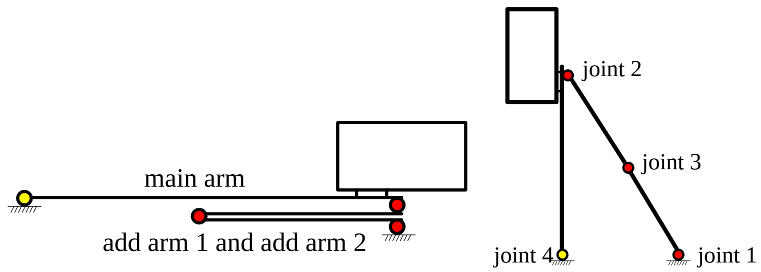


Figure2. Sketch of the deployable arm in stowed and deployed status

This paper aims to increase controllability of the above large flexible antenna by modal optimization. Firstly, Sensitivity analysis of antenna modal frequencies to stiffness of support structure and stiffness of scanning mechanism are conducted respectively. Secondly, Modal simulation results of antenna frequencies are given, influences of scanning angles on moment of inertia and modal frequencies are evaluated, and modal test is carried out to validate the simulation results. All the simulation and test results show that, after modal optimization the modal characteristic of the large deployable antenna meets the controllability requirement well.

2. Sensitivity Analysis of Antenna Frequency

Modal results of the antenna can be obtained by solve the differential equation below:

$$M\ddot{x}+Kx=0 \tag{1}$$

The responding kth modal frequency and modal vector are ω_k and Φ_k respectively, and

$$(K-\omega_k^2 M)\Phi_k=0 \tag{2}$$

Suppose the design variable is X, then

$$\left(\frac{\partial K}{\partial X}-2\omega_k M\frac{\partial \omega_k}{\partial X}-\omega_k^2\frac{\partial M}{\partial X}\right)\Phi_k=0 \tag{3}$$

While $\Phi_k^T M\Phi=I$

The sensitivity coefficient of the kth modal frequency to design variable X is defined as

$$\frac{\partial \omega_k}{\partial X}=\frac{\Phi_k^T}{2\omega_k}\left(\frac{\partial K}{\partial X}-\omega_k^2\frac{\partial M}{\partial X}\right)\Phi_k \tag{4}$$

For the above large deployable antenna, the mass mainly concentrate at the equipment container and mesh reflector parts, stiffness of the whole structure mainly depends on the stiffness of the support structure and scanning mechanism, so sensitivity analysis of antenna modal frequencies to stiffness of support structure and stiffness of scanning mechanism is conducted.

2.1. Stiffness of support structure

Support structure including five parts: two composite material bars (add bar 1 and add bar 2) and three titanium joints (joint 1, joint 2 and joint 3). Bar 1 is connected to the satellite panel by joint 1, and bar 2 is connected to the antenna by joint 2, with joint3 between bar 1 and bar 2. Bar 1, bar 2 and joint 3 can be simplified as a series model. As stiffness of the composite material bars are relatively high, the equivalent stiffness of the support structure is largely depends on stiffness of joint 3. Sensitivity coefficients bar graph of the first six modal frequencies to stiffness of joint 3 is shown in Figure3, the first six modal frequencies of the antenna is most sensitive to stiffness coefficient k1 and k6 of joint 3, which corresponds to the axis tensile stiffness and torsional stiffness of joint 3.

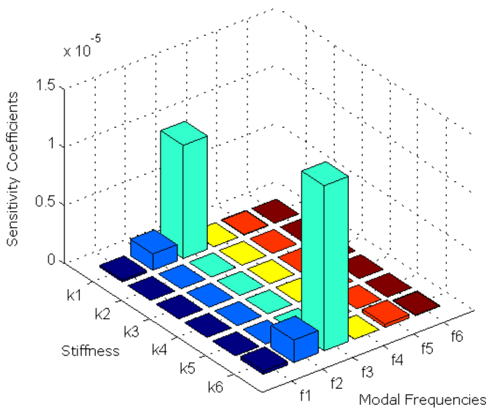


Figure3. Sensitivity coefficients bar graph of the first six modal frequencies to stiffness of joint 3

2.2. Stiffness of scanning mechanism

The scanning mechanism can be move from -10 °to 25 °about pitch axis and from -10 °to 10 °about azimuth axis. As moment of inertia of the antenna is very large, stiffness of the mechanism greatly affects equivalent stiffness of the whole structure. Sensitivity coefficients bar graph of the first six modal frequencies to stiffness of scanning mechanism is shown in Figure4, the 1st mode frequency of the antenna is sensitive to torsional stiffness k26, and the 2nd mode frequency of the antenna is sensitive to torsional stiffness k16, which corresponds to the torsional stiffness about pitch axis and azimuth axis respectively.

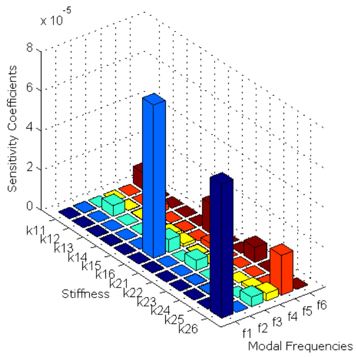


Figure4. Sensitivity coefficients bar graph of the first six modal frequencies to stiffness of scanning mechanism

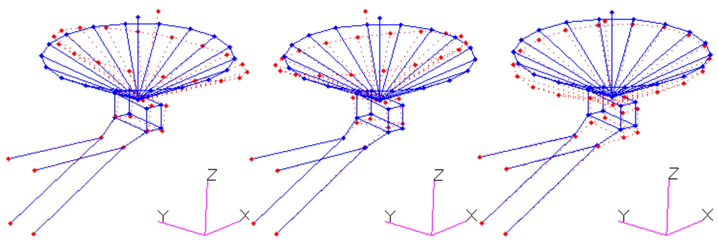
3. Modal Analysis of Antenna Frequency

3.1. Modal Simulation

Base on the sensitivity analysis results, much work has done to optimize the stiffness of support structure and scanning mechanism. Then modal simulation of the antenna is conducted and the simulation results are summarized in table1, the 1st and 2nd modal frequency of the antenna are 1.04Hz and 1.13Hz respectively, and the 1st modal shape shows as the reflector rotates about the pitch axis while the 2nd modal shape shows as the reflector rotates about the azimuth axis.

Table 1. Modal simulation results

Mode	Modal Frequency(Hz)	Modal Effective Mass Fraction					
		TX	TY	TZ	RX	RY	RZ
1	1.04	0.00%	34.00%	0.07%	78.37%	0.07%	41.48%
2	1.13	32.53%	0.00%	0.33%	0.00%	10.35%	0.00%
5	5.61	1.86%	0.75%	64.39%	0.09%	74.53%	0.77%

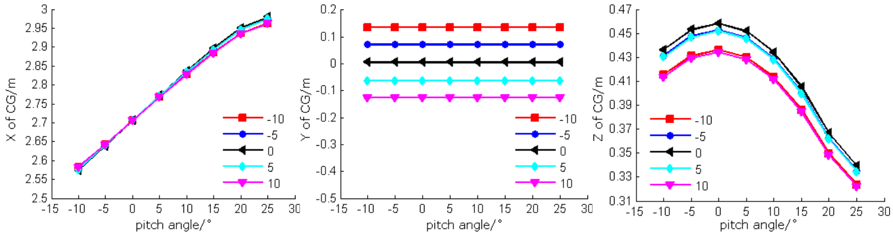


a) Modal Shape along X b) Modal Shape along Y c) Modal Shape along Z

Figure5. Modal shapes of the antenna

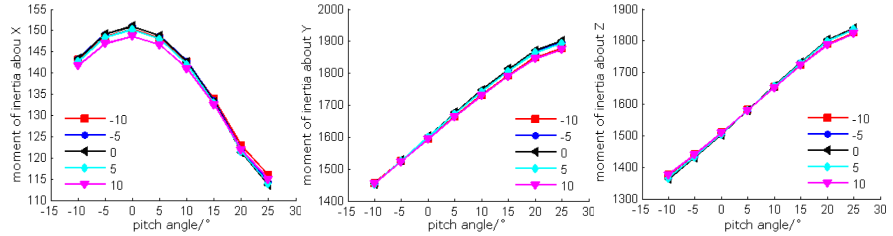
3.2. Relationship between moment of inertia and scanning angles

Rotation of scanning mechanism about pitch axis and azimuth axis would induce angular acceleration, and as moment inertia of the antenna is very large, the acceleration disturbance may result in very large structural response. So it is expected that moment inertia of the antenna could be controlled to be constant among the angle ranges. As shown in Figure6 and Figure7, X of CG and Y of XG are sensitive to pitch angle and azimuth angle respectively, Z of XG reaches its minimum at angle of [25 °, 10 °], and Moment of inertia of the antenna is much more sensitive to pitch angles.



a) X of XG b) Y of CG c) Z of CG

Figure6. CG of the antenna at different scanning angles

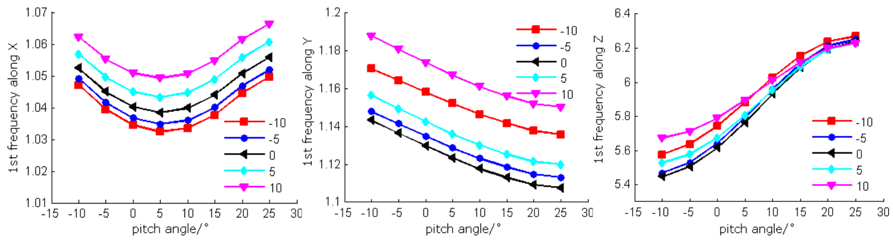


a) Moment of inertia about X b) Moment of inertia about Y c) Moment of inertia about Z

Figure7. Moment of inertia of the antenna at different scanning angles

3.3. Relationship between moment of inertia and scanning angles

The first modal frequencies in X, Y and Z direction of the antenna at different pitch and azimuth angles are shown in Figure8. Compared with the pitch axis, the azimuth axis has more impacts on the modal frequency. While the azimuth axis is 10 °, mo matter how greatly the pitch angle changes, the first modal frequency of the antenna could keep at a relatively high level. Under cases of pitch angles [-10 °,-5 °,0 °,5 °,10 °,15 °,20 °,25 °] combined with the azimuth angles [-10 °,-5, 0 °,5 °,10 °], the minimum modal frequencies in X, Y and Z direction are 1.03Hz, 1.11Hz and 5.45Hz respectively.



a) 1st frequency in X direction b) 1st frequency in Y direction c) 1st frequency in Z direction

Figure8. 1st modal frequencies of the antenna at different scanning angles

4. Modal Test

For validation of the modal simulation results, modal test is carried out at antenna level. Initial forced displacement is applied at edge of the reflector, and released to excite the antenna, also acceleration response data at several typical positions are measured in time domain. The measured time domain data is transformed to frequency domain to obtain the modal shapes, modal frequencies and modal damping ratios of the antenna. The measure equipment is the LMS SCADAS-Ⅲ data acquisition unit, with a very good sensitivity from DC to 51.2KHz. The accelerometers are tri-axial accelerometers by PCB, with frequency range from 0.5Hz to 5KHz, and will not add much additional mass on the test structure.

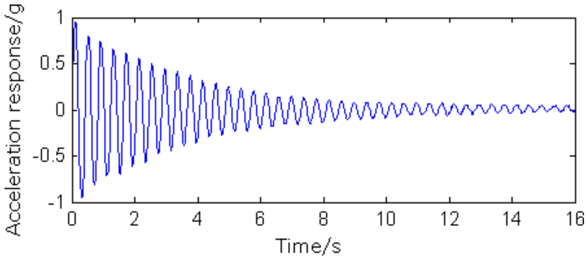
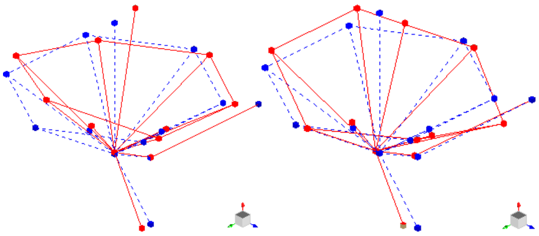


Figure9. Response curve in time domain

Table 2. Modal test results

Mode	Modal result in X direction		Modal result in Y direction	
	Modal frequency/Hz	Modal damping ratio	Modal frequency/Hz	Modal damping ratio
1	1.19	3.57%	1.04	5.27%
2	3.87	0.76%	3.45	1.95%



a) Modal shape in X direction b) Modal shape in Y direction

Figure10. Test results of modal shapes

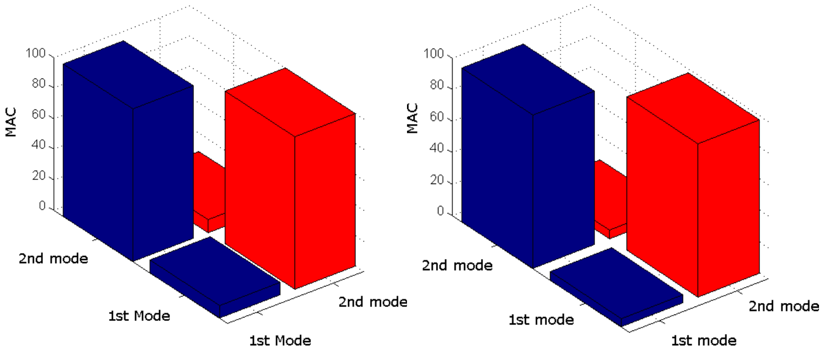


Figure11. MAC of first two modes

5. Conclusion

This paper aims to increase controllability of a large flexible antenna by modal optimization. By sensitivity analysis of antenna frequency to stiffness of support structure and scanning mechanism, the most sensitive design variables are identified, and corresponding structural optimization is done to maximum the modal frequencies. Modal simulation results show that, among the whole rotation angle ranges, the minimum modal frequency in X, Y and Z direction are 1.03Hz, 1.11Hz and 5.45Hz respectively. The following modal test results are in good agreement with the simulation expectation, and the aim to increase controllability of the large flexible antenna is achieved.

References

[1] A Meguro, K Shintate, M Usui, et al. In-orbit deployment characteristics of large deployable antenna reflector on board Engineering Test Satellite VIII[J]. Acta Astronautica, 2009, 65: 1306-1316.
[2] MW Thomson. The Astromesh deployable reflector[C]. IUTAM–IASS Symposium on Deployable Structures: Theory and Application, Cambridge, MA, USA, 1998, 435-446.
[3] D Lu, FL Guan, KG James. Structural optimization and model fabrication of a double-ring deployable antenna truss[J]. Acta Astronautica, 2014, 94: 843-851.
[4] DO Lee, GY Park, JH Han. Experimental study on on-orbit and launch environment vibration isolation performance of a vibration isolator using bellows and viscous fluid[J]. Aerospace Science and Technology, 2015, 45: 1-9.
[5] D Kamesh, R Pandiyan, A Ghosal. Modeling, design and analysis of low frequency platform for attenuating micro-vibration in spacecraft[J]. Journal of Sound and Vibration, 2010, 329(17): 3431-3450.
[6] HA Fujii, Y Sugimoto, T Watanabe, et al. Tethered actuator for vibration control of space structures[J]. Acta Astronautica, 2015, 117: 55-63.
[7] SA Lane, SL Lacy, V Babuska, et al. Active vibration control of a deployable optical telescope[J]. Journal of Spacecraft and Rockets, 2008, 45(3): 568-586.
[8] A Sharma, R Kumar, R Vaish, et al. Active vibration control of space antenna reflector over wide temperature range[J]. Composite Structures, 2015, 128: 291-304.
[9] TP Sales, DA Rade, LCG de Souza. Passive vibration control of flexible spacecraft using shunted piezoelectric transducers[J]. Aerospace Science and Technology, 2013, 29(1): 403-412.